Heavy Quarks and the Strong Potential

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Four forces determine the structure of the world:

Gravity, Electromagnetism, Strong, and Weak.

This is a talk about the Strong Force. As it binds quarks to form nucleons and nuclei, the strong force is to a large degree responsible for the patterns that we find in nature.

In particular it is an experimentalist's perspective on

- the status of our understanding of the strong force,
- particular fundamental structures---heavy quark bound states---that have been useful in probing certain features of the theory; and
- why proton-proton collision (the LHC!) is important for a comprehensive understanding of strong interactions.

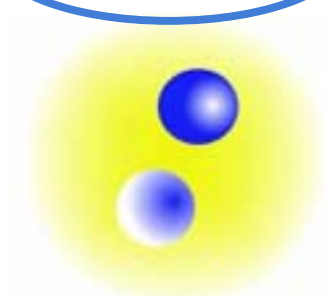
Facts to keep in mind…

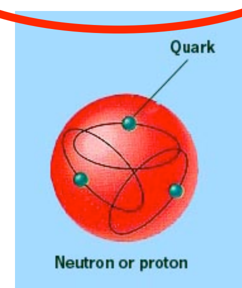
- The Strong Force is the strongest force. It holds the nucleus together, overcoming electrostatic repulsion of the constituent protons. Its range is short, just 10^{-15} m, and this sets the radius of a typical nucleus.
- As is usual in field theory, the force is transmitted through a propagator particle. The propagator of the strong force is the gluon….it "glues" the nucleus together.
- The nucleus is composed of protons and neutrons, but these are made of quarks, so we can think of the nucleus as a bag of quarks exchanging gluons.

some facts, continued…

- The principal quarks in the proton and neutron are types "up" and "down." These are all that's needed to build the nuclei of normal elements. But there are 4 more types of quarks known to exist, able to be produced in cosmic ray collisions and particle accelerators and surely existing since the early universe.

- As far as we know, quarks only bind in two forms: quark -antiquark pairs ("mesons") and 3-quark bundles ("baryons"):

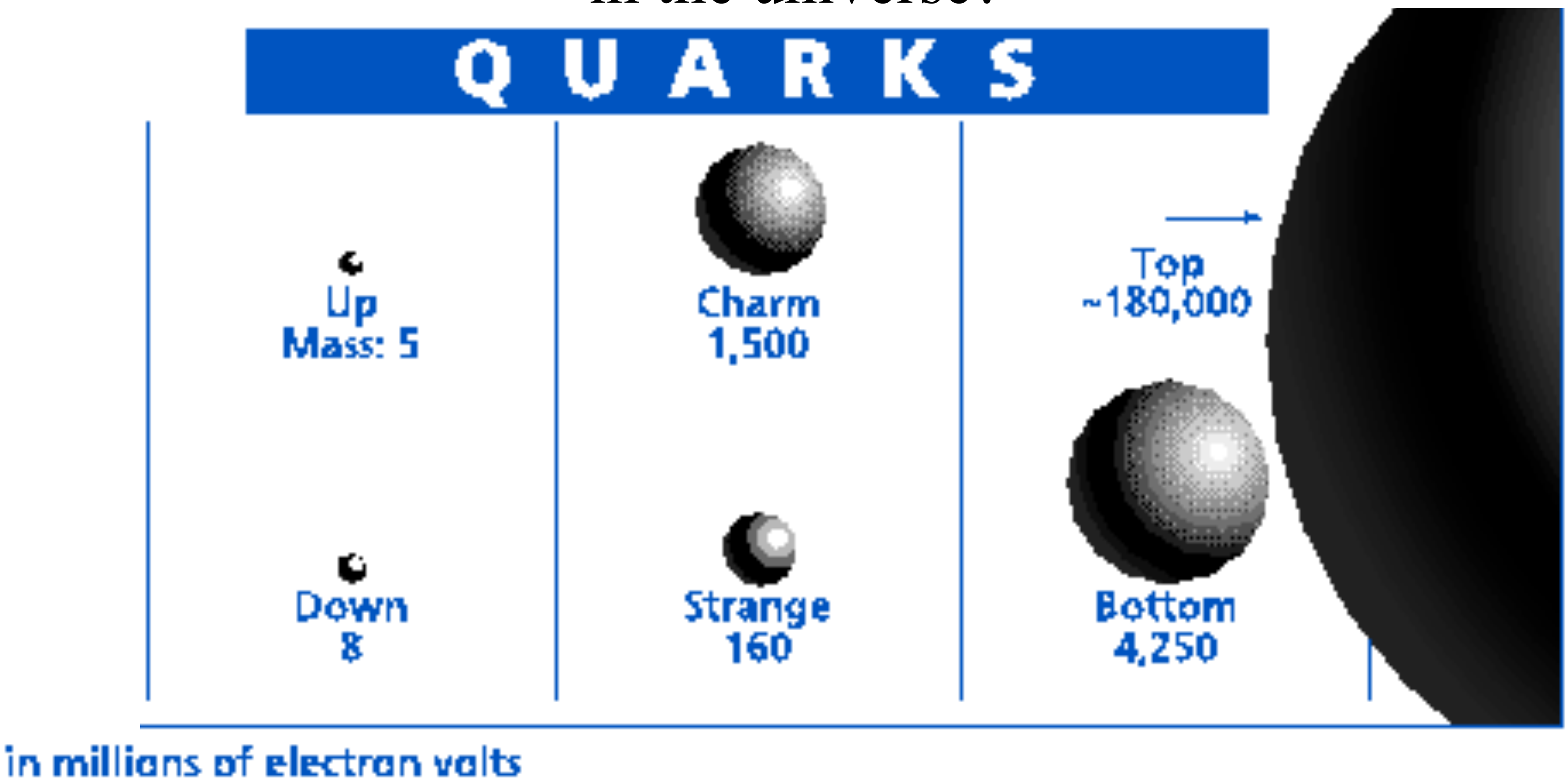




however more complicated (color singlet) bound states are not excluded.

Something puzzling about quarks…

The common ones are light. The less common are 20 to 20000 times heavier (but still dimensionless!) What does this pattern mean? What role do these heavy quarks play in the universe?

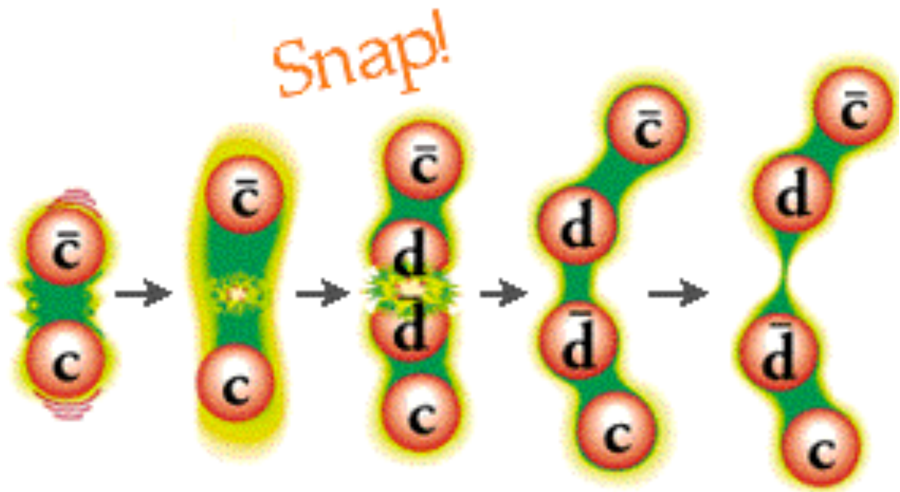


The strong force differs from the electromagnetic and gravitational forces in an important way…

The electrical and gravitational forces get *weaker* ($\sim r^{-2}$) as the distance between particles increases:

$$F_{elec} = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{r^2} \quad \text{and} \quad F_{grav} = G\frac{m_1 m_2}{r^2}$$

The strong force gets *stronger* with distance.



This effect causes *confinement*: "no free quarks." Quarks are permanently confined in bound states.

The underlying cause is an unsolved problem after 30 years. Proposed mechanisms‡ include an analog to the Meissner effect in which quarks are confined by an electric flux tube in a condensate of magnetic monopoles.

‡A good review: R. Alkofer and J. Greensite, J. Phys. G: Nucl. Part. Phys. 34 (2007) S3-S21.

Confinement makes *measurements* challenging!

The fundamental processes that we want to understand take place between individual pointlike partons, but before these reach detectors, they form bound states. Direct measurements of the interacting particles are impossible.

This makes *theoretical calculations* of strong processes difficult too.

Quantum mechanics relies on perturbation theory to predict physical observables such as cross sections. This usually takes the form of a mathematical series, in which each term provides an increasingly smaller correction and is proportional to the coupling (*strength of the force*) raised to a power determined by the term's place in the series. It looks something like $A = \varepsilon^0 A_0 + \varepsilon^1 A_1 + \varepsilon^2 A_2 + \ldots$

Where the coupling is large, *convergence is suspect.* A large regime of strong interaction processes see strong couplings to which perturbation theory cannot be applied. An example is the process (*"hadronization"*) that binds quarks into observable states.

The theory of the strong force is Quantum Chromodynamics (QCD). Despite calculational challenges, QCD has been very successful. QCD is in many ways modeled on QED, the theory of electromagnetism. However whereas QED has been shown to predict phenomena "to the 11th decimal place," some QCD measurements are precise only to within 10%, and quantifying some theoretical systematics is challenging.* So there's plenty of work for an experimenter to do.

For example, the exact form of the strong potential, the Strong analog to

$$V_{elec} = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{r}$$

is not known.

*J. Pumplin et al., JHEP 0207:012 (2002).

A important test of QCD is its ability to predict the energies of observed bound states.

Where perturbative expansion is problematic, several approaches have been taken to this problem…

- **Lattice calculations** ---introduction of a cutoff to control divergences when two fields are evaluated at the same point. Could be a minimum distance between 2 local fields: spacetime becomes discrete. Special problem for bound states of heavy (large mass m) quarks: they move slowly---small velocity v. Predictions are limited by computational power associated with lattice extent (large compared to $1/mv^2$) and granularity (small compared to $1/m$).

- One can try **Effective Field Theory** (EFT) instead...a quantum field theory in which different scales are factorized, leaving adequate degrees of freedom to describe phenomena in a specific range. Typically an EFT has *a potential* which encodes the effect of degrees of freedom that have been integrated out from full QCD.

These potentials can be classified as "non-QCD -like" (phenomenological) and "QCD-inspired." Here are some examples:

At short distances, lowest order perturbation theory gives a Coulomb-like potential for one-gluon exchange

$$V(r) = -\frac{4}{3}\frac{\alpha_s(r)}{r}$$

but *this does not include confinement. Another term must be added…*

Experimentally, $q\bar{q}$ production typically occurs at an energy scale 1 GeV (typical hadron mass) at a separation of 1 fm (typical hadron size). *So at long distances,* one-gluon exchange can be replaced by bunched "color flux tubes" with linear energy density σ:

$$V(r) = \sigma \cdot r$$

This gives the "Cornell potential":

$$\sigma \equiv \frac{\Delta E}{\Delta r} \cong 1 \frac{\text{GeV}}{\text{fm}} \cong 0.18\,\text{GeV}^2$$

Spin-*independent* features of $q\bar{q}$ spectroscopy have been shown to be described by this form.

E. Eichten et al., Phys. Rev. D 17, 3090 (1978).

Other phenomenological spin-independent potentials tuned to match charmonium ($c\bar{c}$) and bottomonium ($b\bar{b}$) spectra include the

- Logarithmic potential,
  - *Phys. Lett. B 71, 153 (1977)*

$$V(r) = A\log(r/r_0)$$

- Richardson potential,
  - *Phys. Lett. B 82, 272 (1979)*

$$V(q^2) = -\frac{4}{3}\frac{12\pi}{33-2n_f}\frac{1}{q^2}\frac{1}{\ln(1+q^2/\Lambda^2)}$$

- Buchmüller-Tye potential,

$$V(r<0.01fm) = -\frac{16\pi}{25}\frac{1}{r\ln(1/\Lambda^2 r^2)}\left[1+\left(2\gamma_E+\frac{53}{75}\right)\frac{1}{\ln(1/\Lambda^2 r^2)}-\frac{462}{625}\frac{\ln\ln(1/\Lambda^2 r^2)}{\ln(1/\Lambda^2 r^2)}\right]$$

  - *Phys. Rev. D 24, 132 (1981)*

- Martin potential,
  - *Phys. Lett. B 93, 338 (1980).*

$$V(r) = A(r/r_0)^{\alpha}$$

- The QCD-inspired spin-dependent[‡] and velocity-dependent potentials have been written down, for example:

$$V_{sd} = \left(\frac{\vec{S}_1 \cdot \vec{L}_1}{4m_1^2} - \frac{\vec{S}_2 \cdot \vec{L}_2}{4m_2^2} \right) \left[\frac{1}{R} \frac{d\varepsilon(R)}{dR} + \frac{2}{R} \frac{dV_1(R)}{dR} \right] + \left(\frac{\vec{S}_2 \cdot \vec{L}_1}{2m_1 m_2} - \frac{\vec{S}_1 \cdot \vec{L}_2}{2m_1 m_2} \right) \frac{1}{R} \frac{dV_2(R)}{dR}$$
$$+ \frac{1}{6m_1 m_2} \vec{S}_1 \cdot \vec{S}_2 \vec{\nabla}^2 V_2(R) + \frac{1}{12 m_1 m_2} (3\vec{S}_1 \cdot \hat{R} \vec{S}_2 \cdot \hat{R} - \vec{S}_1 \cdot \vec{S}_2) V_2(R)$$

[‡] *E. Eichten and F. Feinberg, Phys. Rev. D 23, v.11, 2724 (1981).*

Each proposed potential function leads to a hypothesized spectrum. For example, from Godfrey and Isgur, Phys. Rev. D 32, 189 (1986):

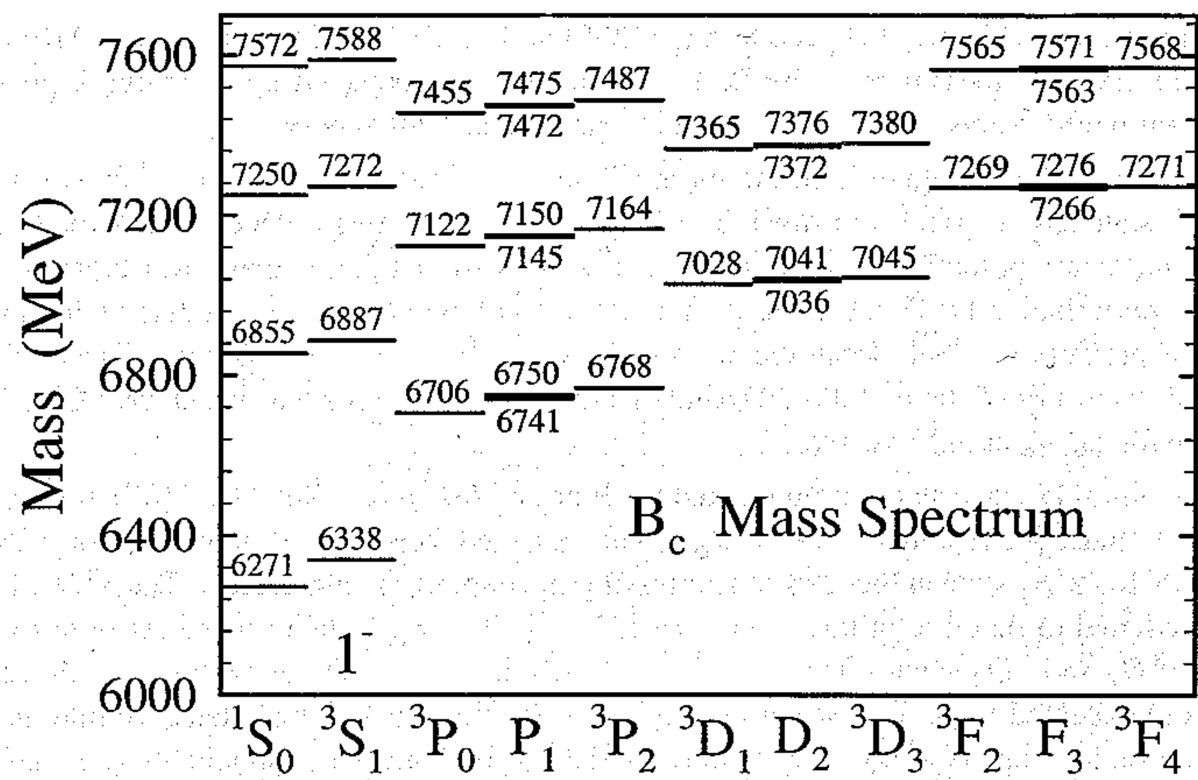


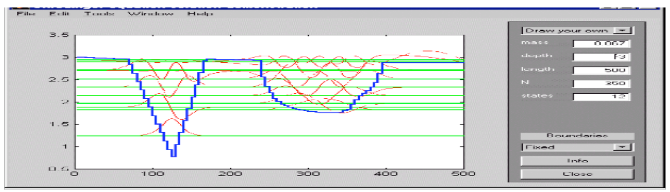
Fig. 3.9: B_c spectrum.

3.2.3 B_c mesons

The B_c mesons provide a unique window into heavy quark dynamics. Although they are intermediate to

So a reasonable experimental goal is to map the strong potential.

We know that the detailed shape of a potential determines the energies at which its states are bound.



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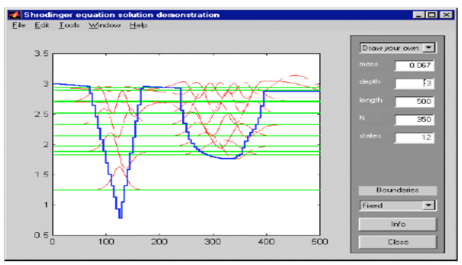

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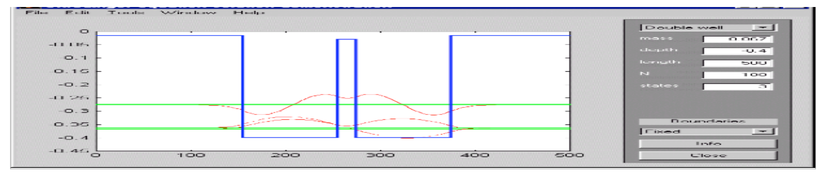

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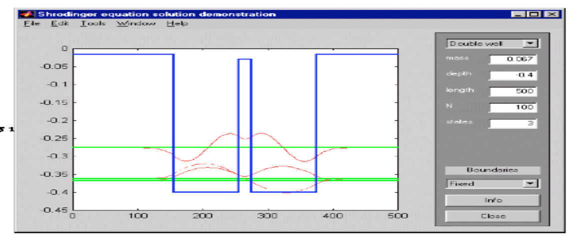

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Heavy quark bound states are key to elucidating the strong potential.

Bound states of light quarks can be modeled by a perturbed Coulombic spectrum, but this can't be complete:

the spectrum of $c\bar{c}$ and $b\bar{b}$ states is known and is not Coulombic.

The ideal laboratory for mapping the strong potential...the B_c system: bound states of one charm and one anti-bottom quark (or their antiparticles):

Part of the reason why B_c is a good laboratory for comparing data to theory on the shape of the strong potential is:

- modeling the binding of a two-body ($q\bar{q}$) system is easier than modelling three bodies (qqq)---so start with a meson.

- The heavier the better, to suppress relativistic effects---but $t\bar{t}$ cannot form, because top quarks decay before binding.

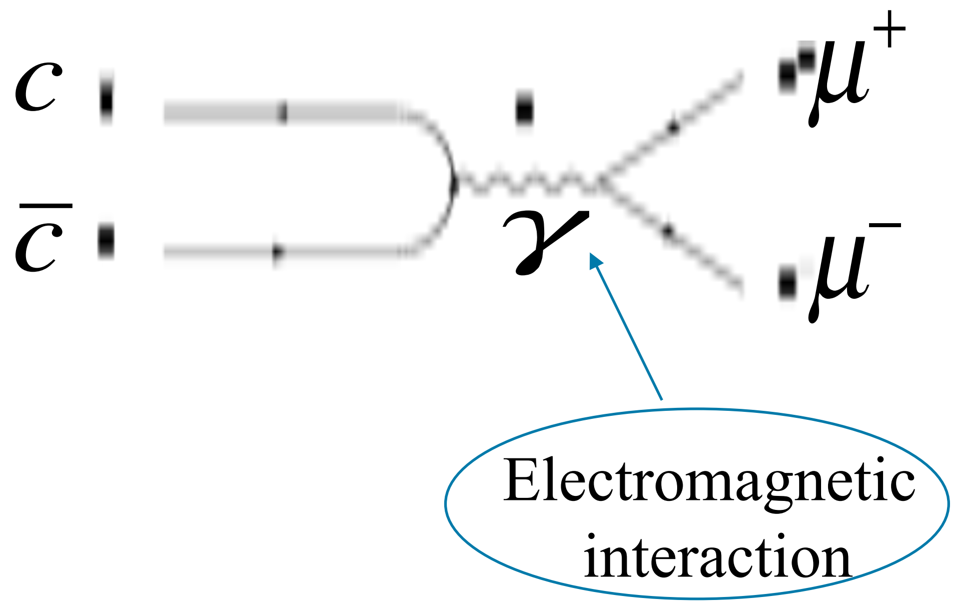
But the *main reason** uses the fact that particle decays can be mediated by any of the forces but *each force introduces its own characteristic time to the process*:

Weak decays typically require	10^{-12} sec
Electromagnetic:	10^{-20} sec
Strong:	10^{-23} sec

*C. Quigg, FERMILAB-CONF-93/257-T

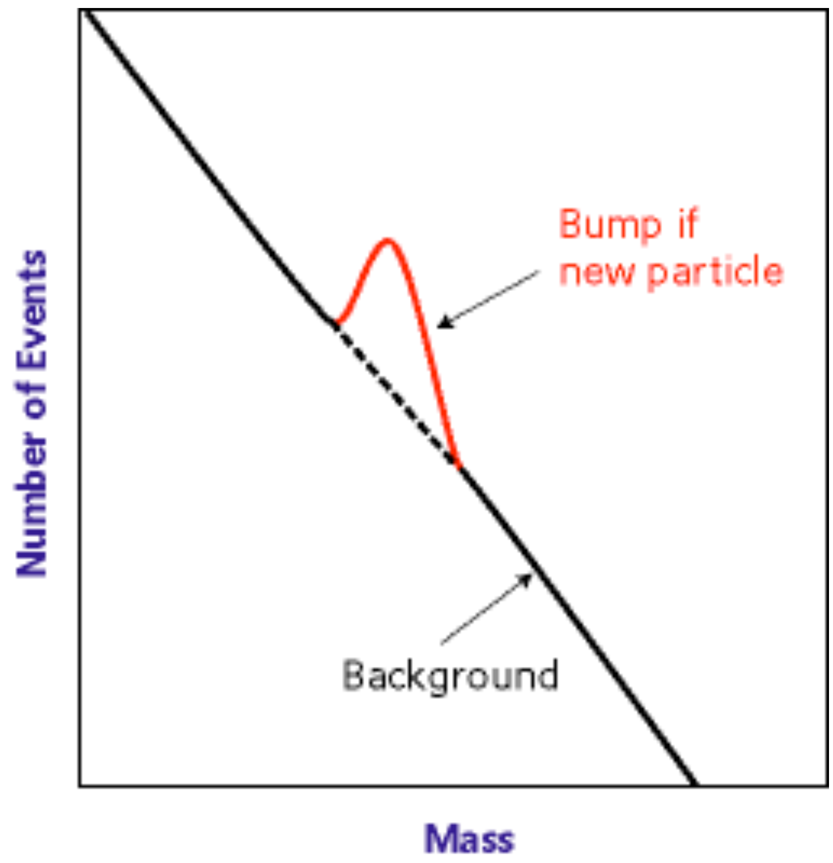
So:

- If we used $b\bar{b}$ or $c\bar{c}$ mesons, they would bind but decay rapidly ($\Delta t \sim 10^{-20}$-10^{-23} seconds) by annihilation...



- Due to the uncertainty principle, $\Delta E \Delta t \geq \hbar / 2$, small Δt means $b\bar{b}$ or $c\bar{c}$ resonance widths ΔE are large.

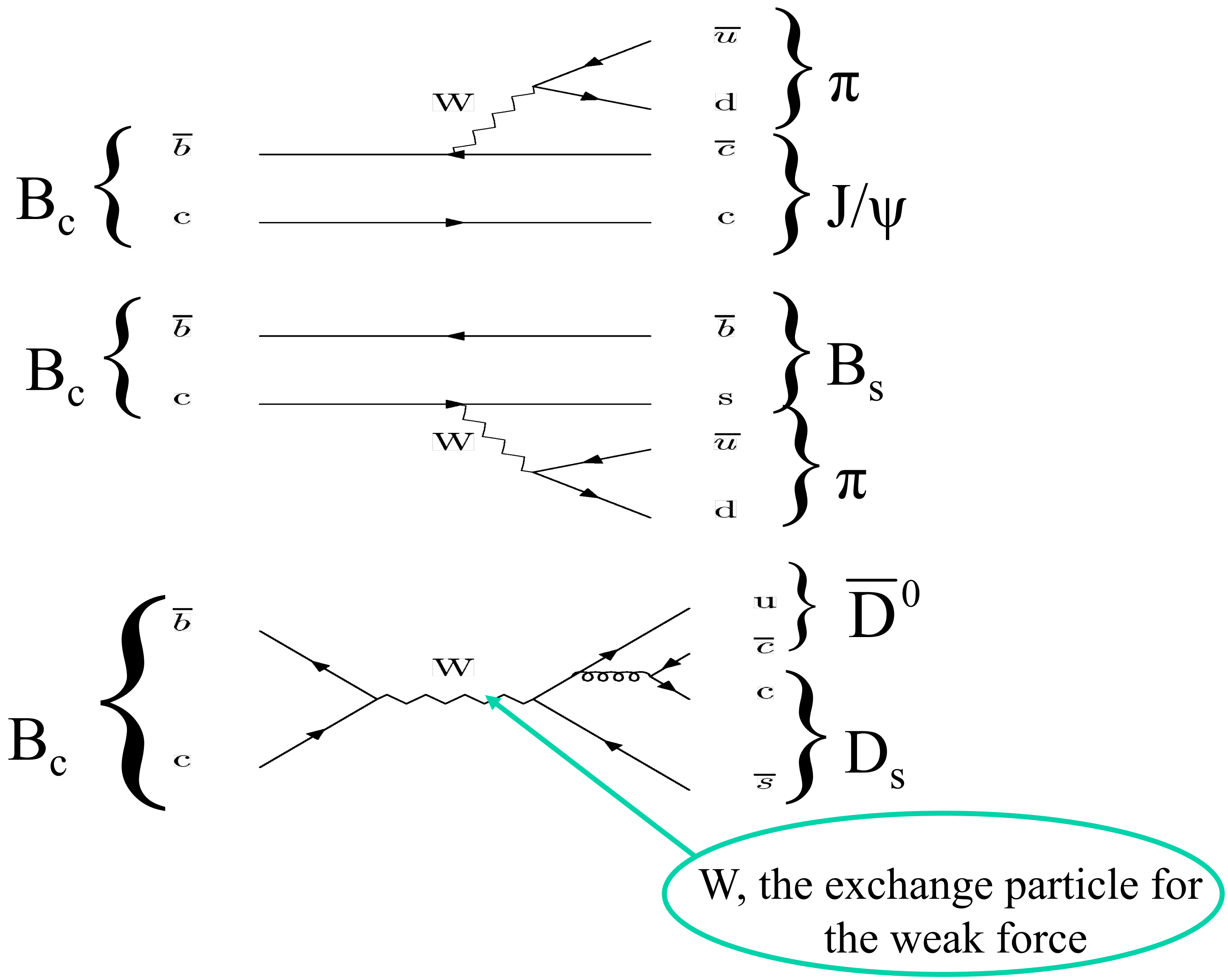
But the wider a peak, the poorer the resolution on its mass, and the harder to distinguish it from background…



- We want a narrow resonance for precision measurement of the mass. We want a resonance that decays weakly.
- B_c cannot decay through the strong and electromagnetic forces because those conserve quark type ("flavor") which prevents the two flavors (*b* and *c*) of the B_c from annihilating. B_c must decay weakly.

B_c should be narrow---providing a precise mass value.

Examples of B_c decays:



The B_c has a high mass...about **6 GeV**:

6 times heavier than the proton...

so it can only be produced at the highest energy colliders.
Precision measurements of it and its excited states B_c^* should provide a map of the strong potential.

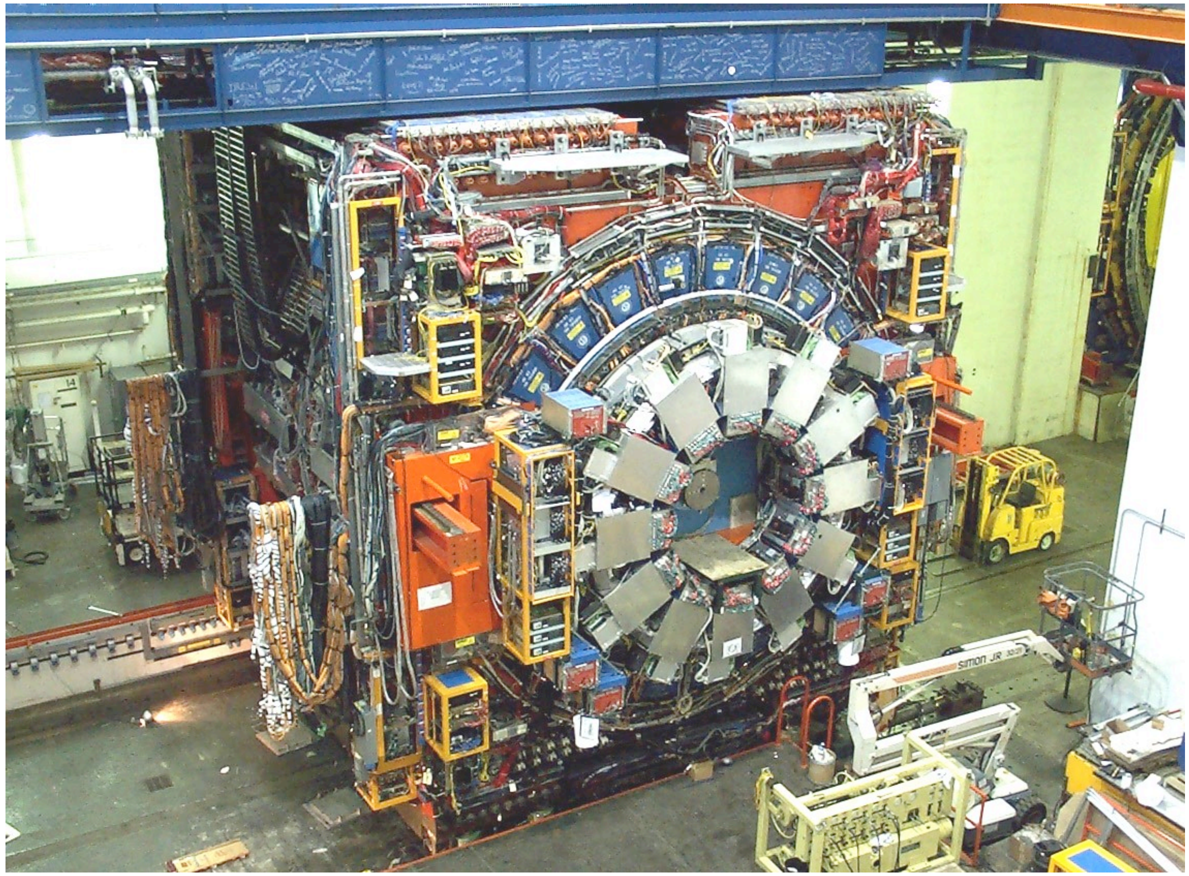
The ground state of the B_c system was discovered* in 1998 at the Fermilab Tevatron Collider…

on the basis of 20 events (occurrences) extracted by the CDF Experiment from almost a decade's worth** of data.

*F. Abe et al., PRL 81, 2432 (1998).

**110 pb^{-1}

The precision mass measurement* did not occur until 2005
(again, CDF)

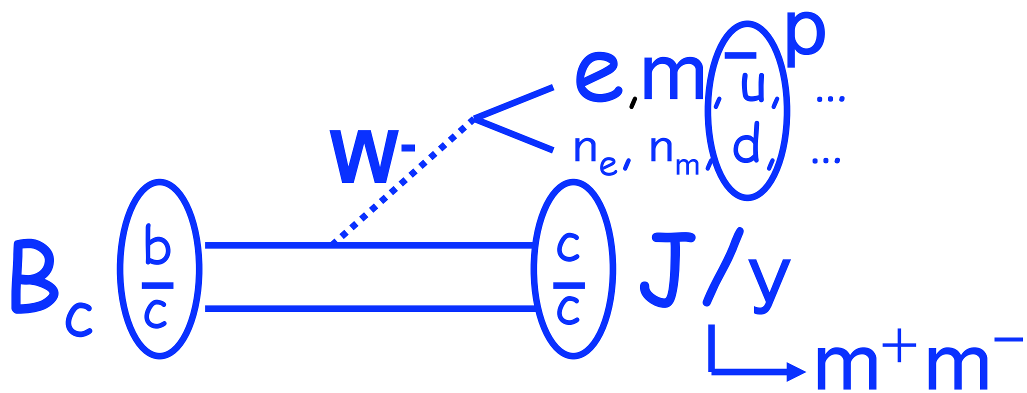


when the particle was for the first time "fully reconstructed":
all of its decay products were observed, so its energy, mass,
and momentum could be simultaneously inferred.

*A. Abulencia et al., PRL 96, 082002 (2006).

The complete reconstruction used the decay

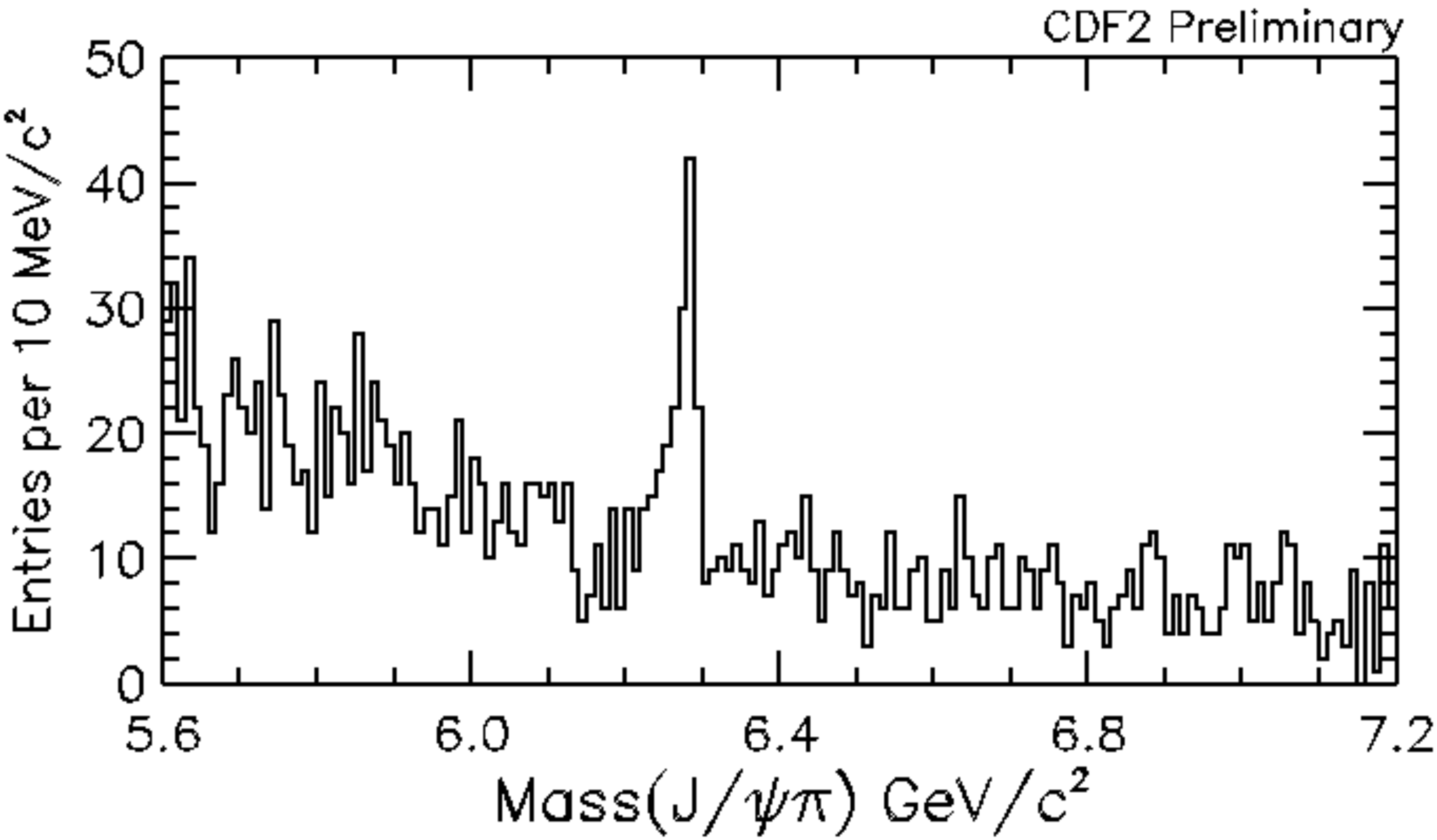
$$B_c^+ \rightarrow J/\psi\pi^+, \quad J/\psi \rightarrow \mu^+\mu^-$$



…14.6 ± 4.6 events observed.

In May 2008 this was updated* with 108 more events from another near-decade** of collisions. The result:

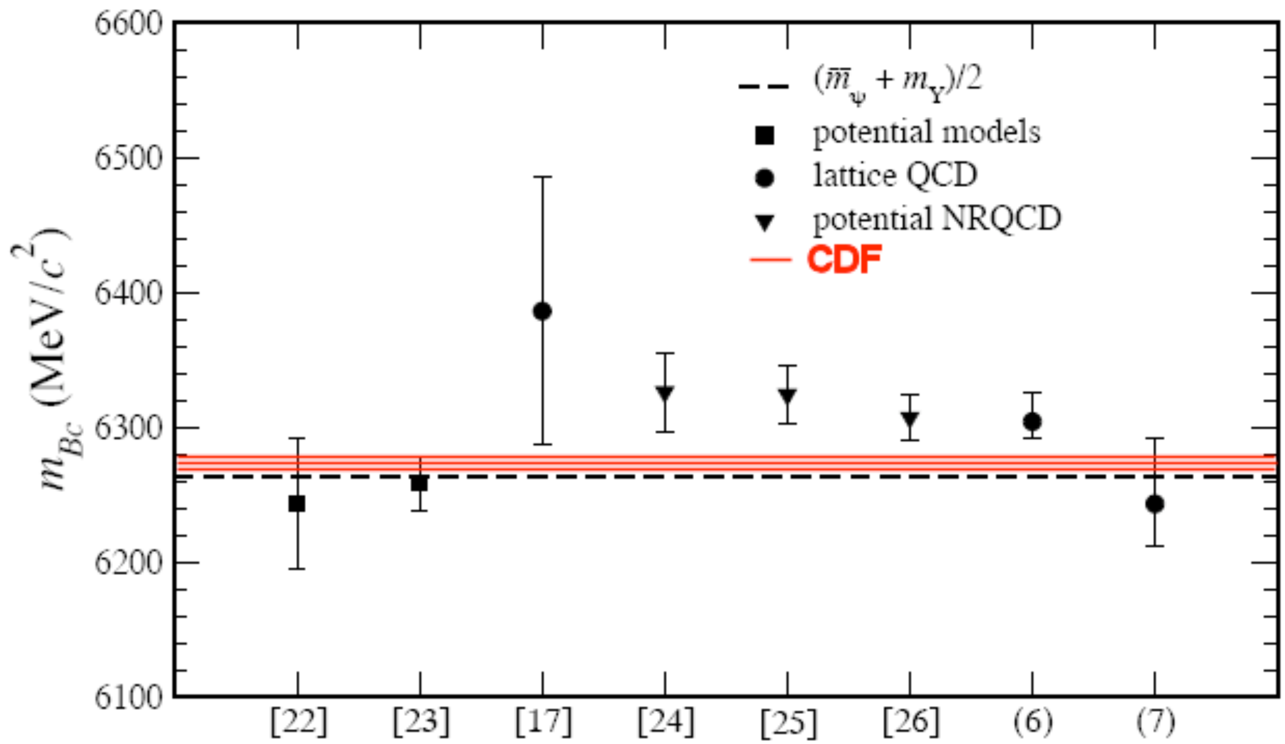
mass (B_c) = 6275 ± 2.9 ± 2.5 MeV/c^2.



*T. Aaltonen et al., PRL 100, 182002 (2008).

**2.4 fb^{-1}.

How does this compare with theory?



It challenges all of them!

$$\text{mass }(B_c)_{CDF} = 6275.2 \pm 2.9 \pm 2.5 \text{ MeV}/c^2$$

$$\text{mass }(B_c)_{LATTICE} = 6304 \pm 12 \,^{+18}_{-0} \text{ MeV}/c^2$$

I.F. Allison et al., PRL 94, 172001 (2005)

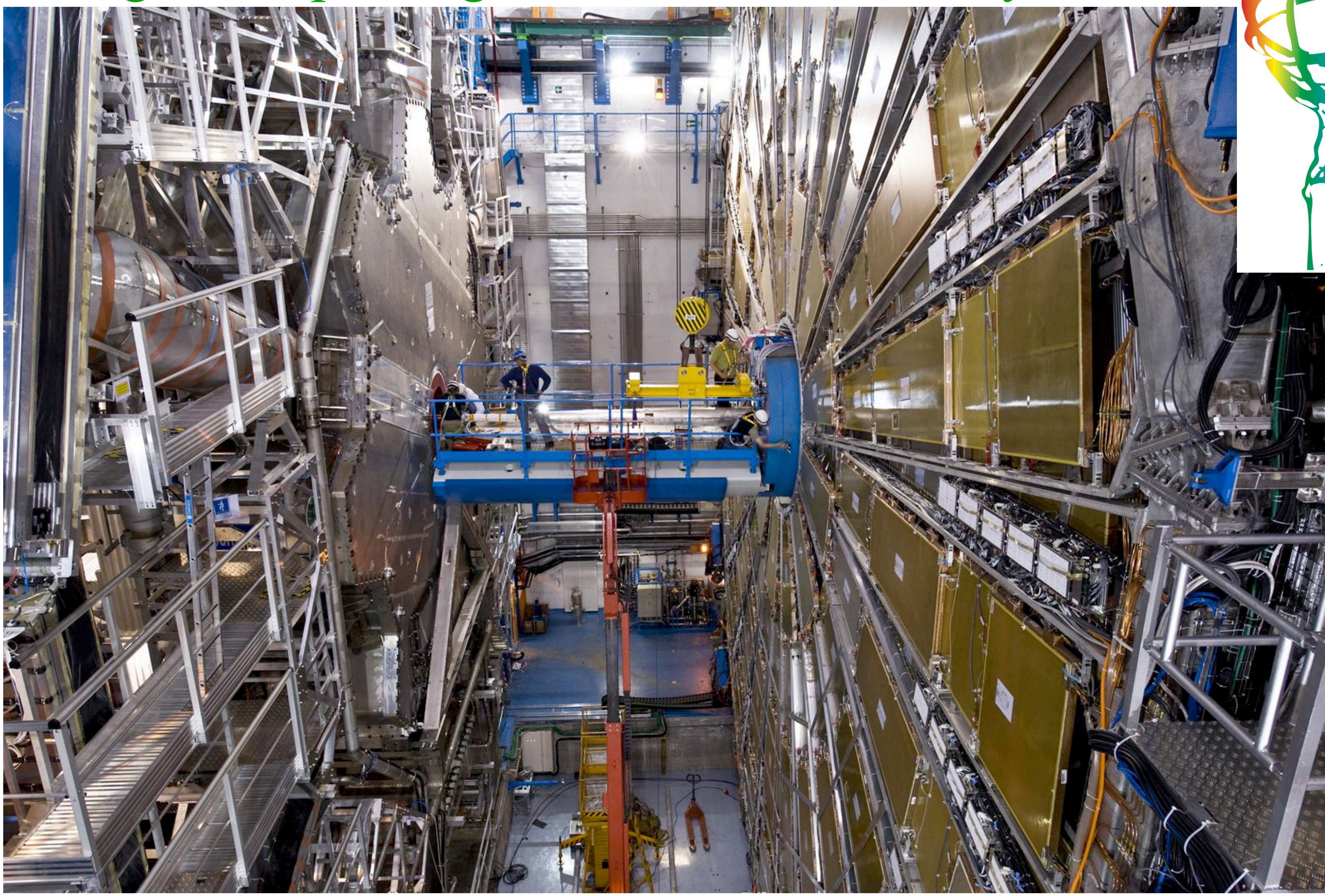
This precision measurement of the B_c mass provides the baseline against which models of the strong potential can be calibrated.

But to map the shape of the potential, we need to know what other stationary states it supports, and we need precision mass measurements of them.

So we need the excited states B_c^* too.

To see the excited states, we need more energy and a higher rate of collisions. The Large Hadron Collider provides proton-proton collisions at center-of-mass energy 10 TeV (compare Tevatron's 2 TeV) and, eventually, 30 x Tevatron luminosity.

Our preliminary studies predict $44 \pm 5 \;\; B_c \rightarrow J/\psi\pi$ events in the first 1 fb^{-1} (about one year) of ATLAS data, and a signal surpassing CDF's in less than 2 years.



A comparable number of B_c^* should be available. How to find them in the ATLAS data?...

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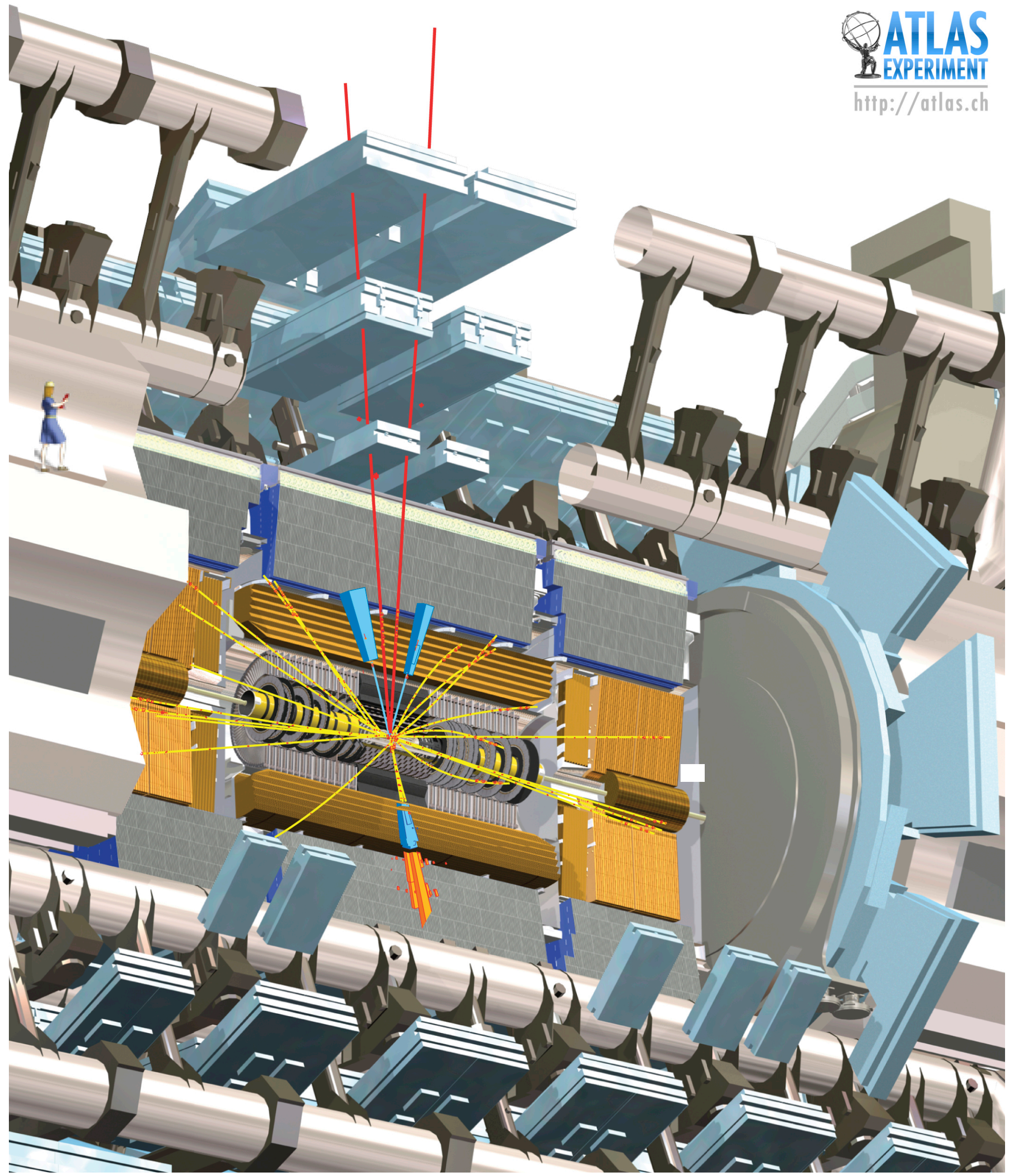
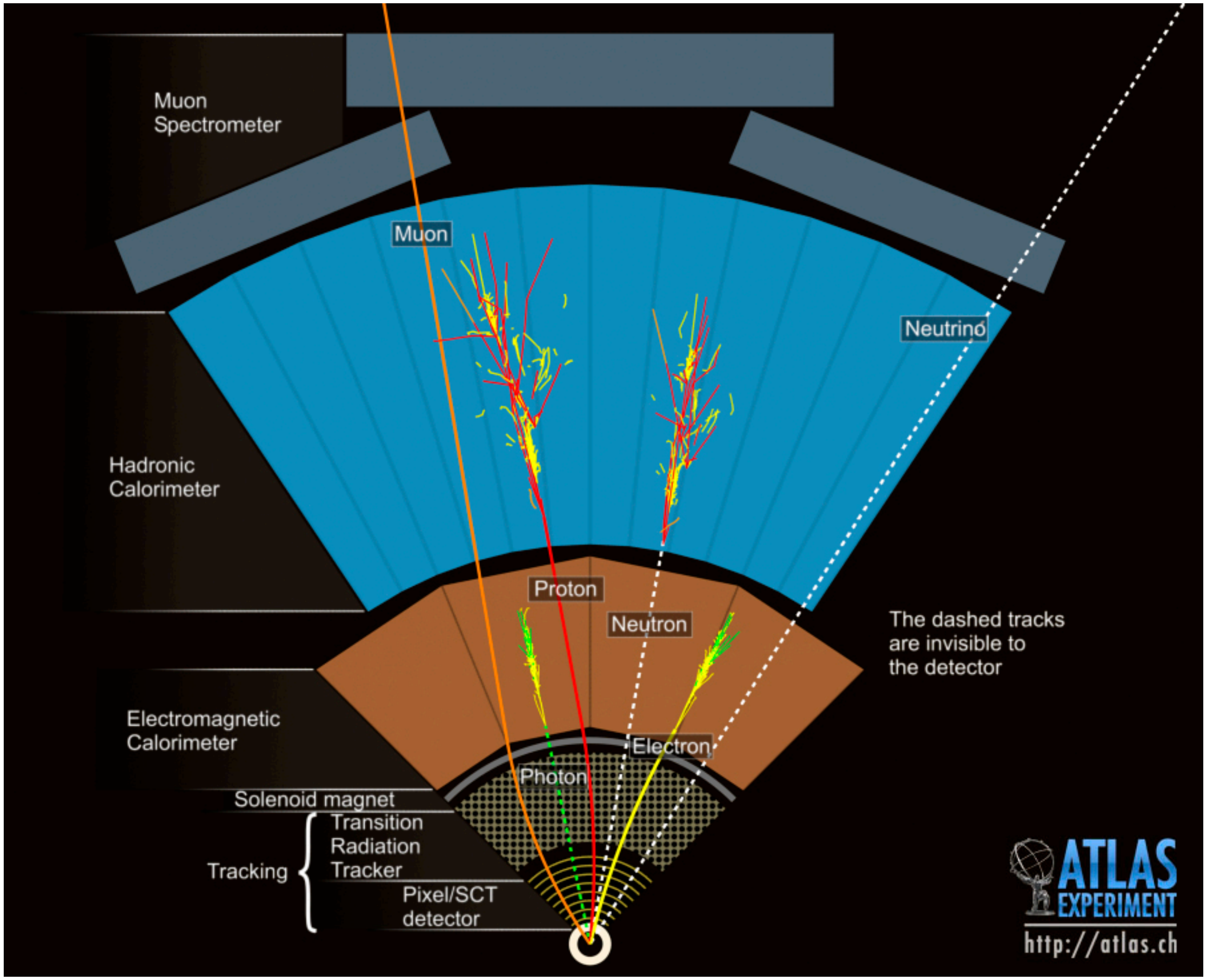
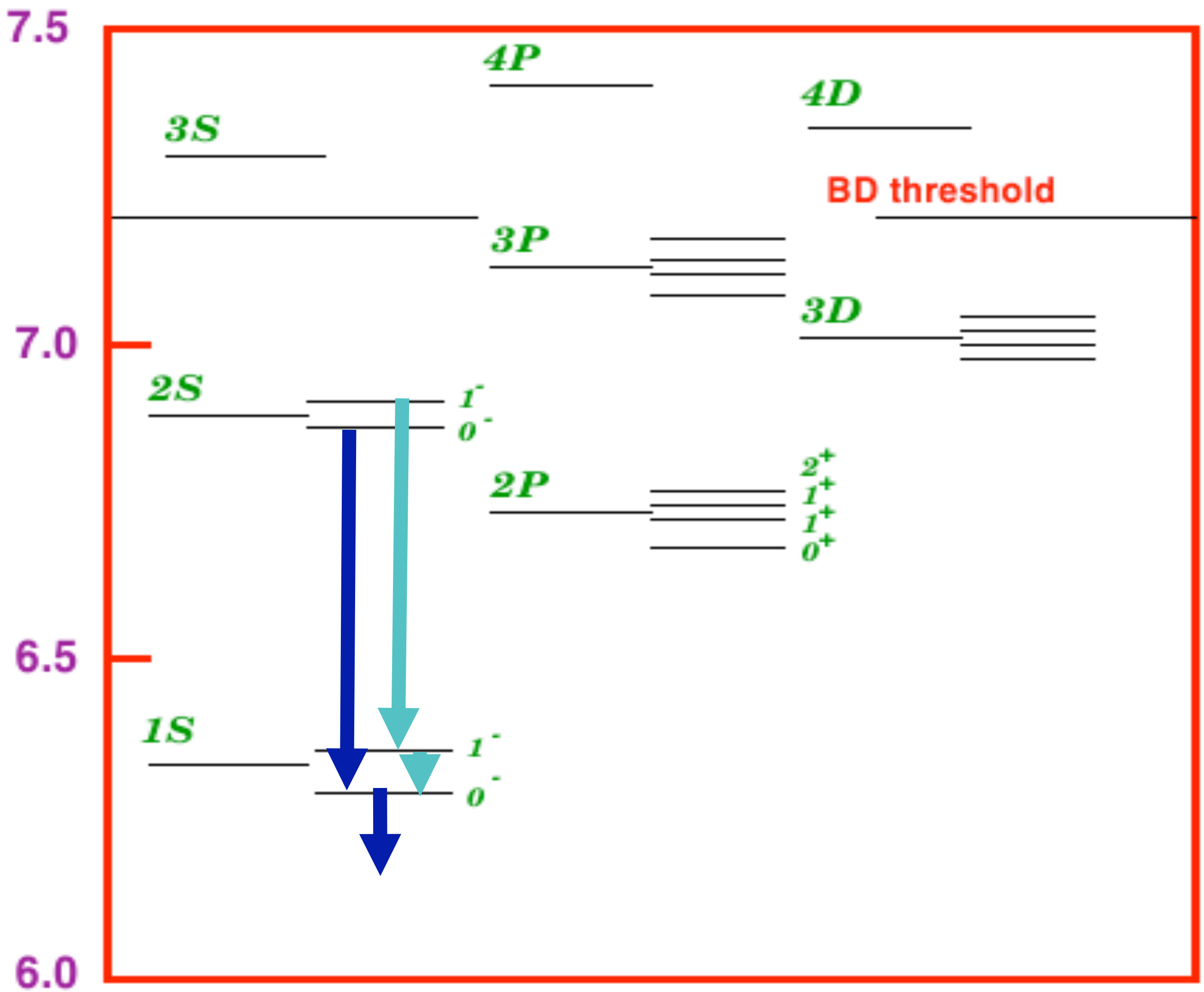
A typical event in ATLAS will produce electronic signals that can be reconstructed as tracks in a series of nested detectors.



This is a beam's eye view of a few sections of the cylindrical barrel. Each detector subsystem images a different property of the particle (its point of origin, momentum, energy, etc.)



We'll begin our reconstruction of the excited states with the lowest, through its channel $B_c^* \to B_c \pi\pi$ *:*



sta
1^1
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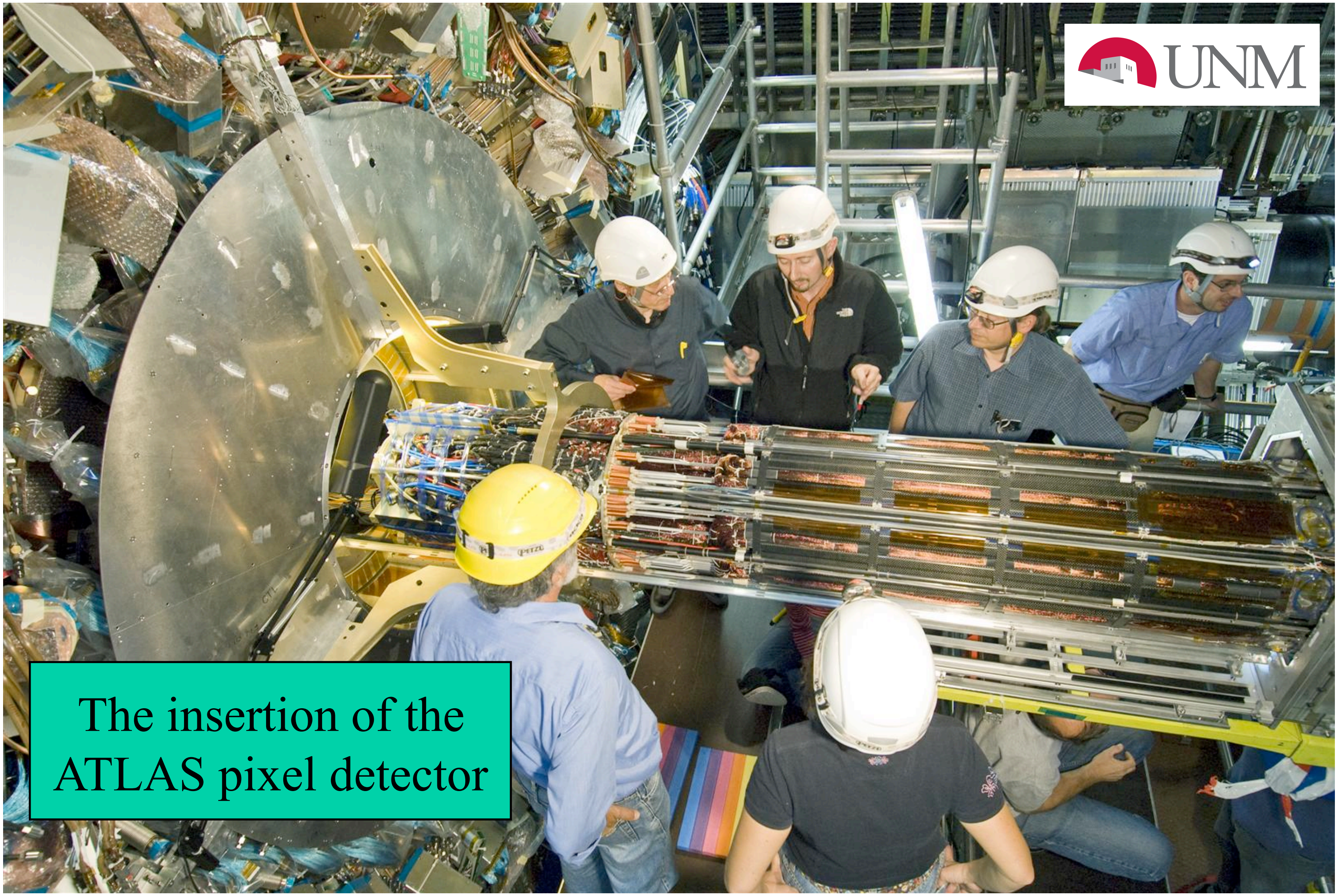
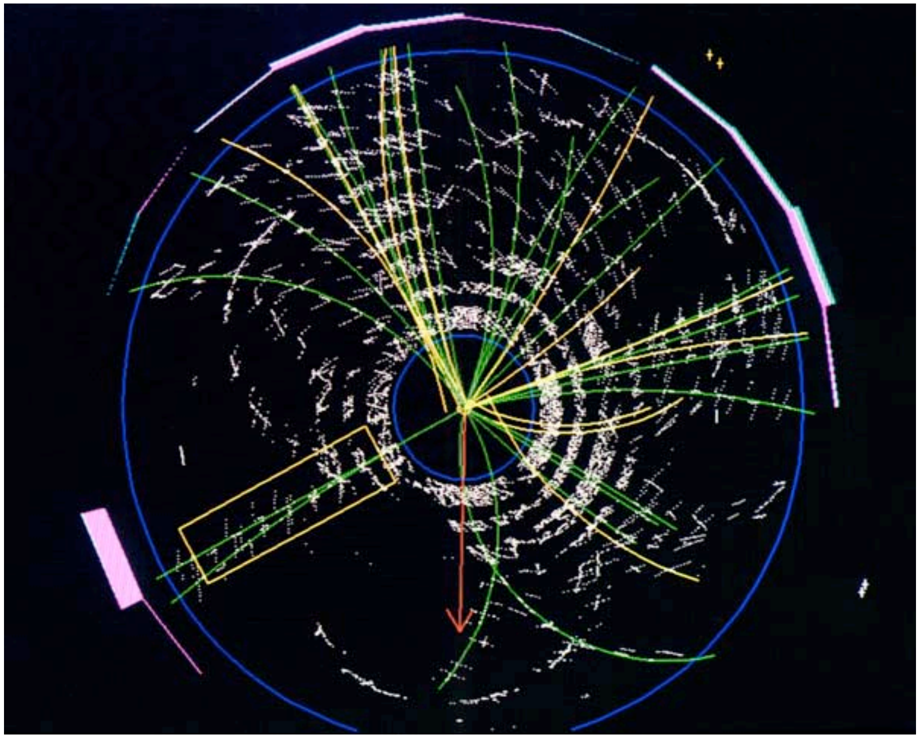
That channel can be understood early in the run primarily through information in one subsystem: the tracker

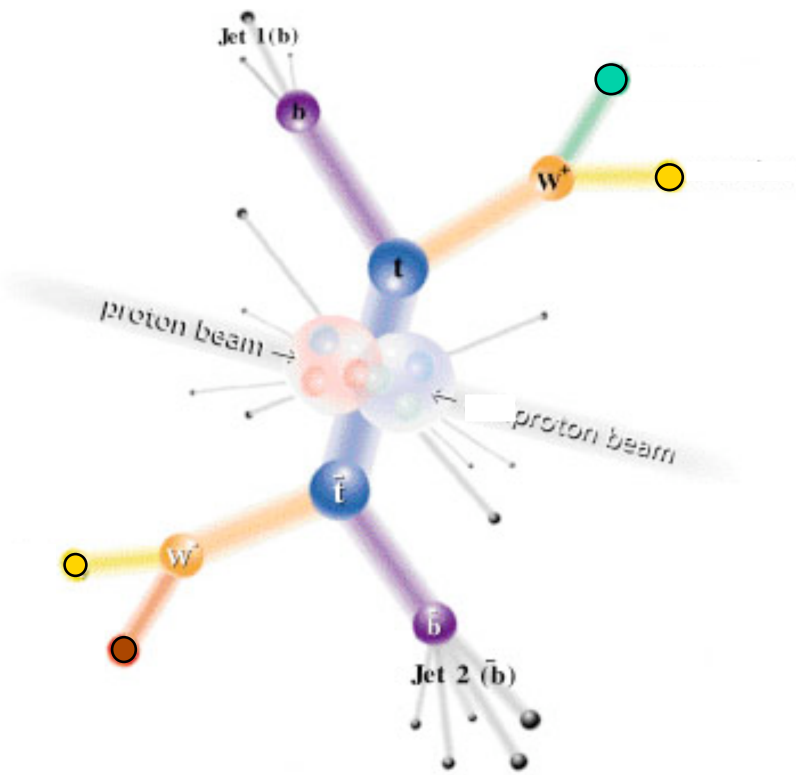


The insertion of the ATLAS pixel detector

The tracker provides information on:

- Particle momentum: from track curvature in the B field, based on helices fit to points where track traverses each detector layer.





- The presence of short-lived rare particles: from reconstructed secondary vertices

A few conclusions…

- There is even more to see at the LHC than the Higgs.
- The opportunity to deepen our understanding of the Strong Force has never been better.
- B_c studies are challenging QCD theory already.

and…

The future is bright!

backup slides…

Comparison of phenomenological potential models (E. Eichten, SLAC Report #267 (1983).

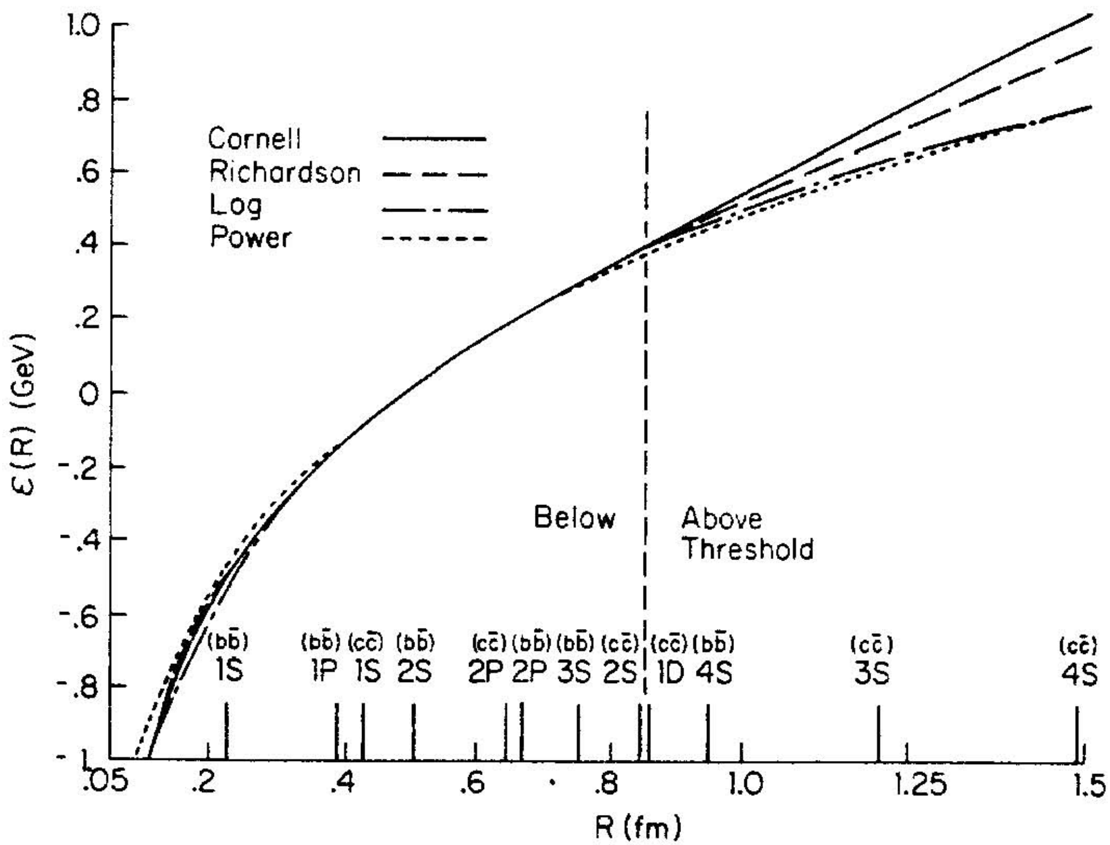


Figure 1: Phenemological Potentials for the Q $\bar{Q}$ System. The RMS radii of the observed c $\bar{c}$ and b $\bar{b}$ states are indicated by markers.

Motivation for Richardson potential:

•From analogy to QED we expect $V(|\vec{q}^{\,2}|) = -\frac{4}{3}\frac{\alpha_s}{|\vec{q}^{\,2}|}$

•but this does not include confinement, so choose a $|q^2|$ dependent function for α_s:

$$\alpha_s(|\vec{q}^{\,2}|) = \frac{12\pi}{33-2n_f}\frac{1}{\log(1+\frac{|\vec{q}^{\,2}|}{\lambda^2})}$$

•As $|q^2|$ becomes of order λ^2, $\alpha_s \rightarrow 1$: theory becomes non-perturbative.

Motivation for Buchmuller-Tye potential:

•begin with the Breit-Fermi Hamiltonian which describes spin-dependent forces in QED and can be derived from classical electrodynamics.

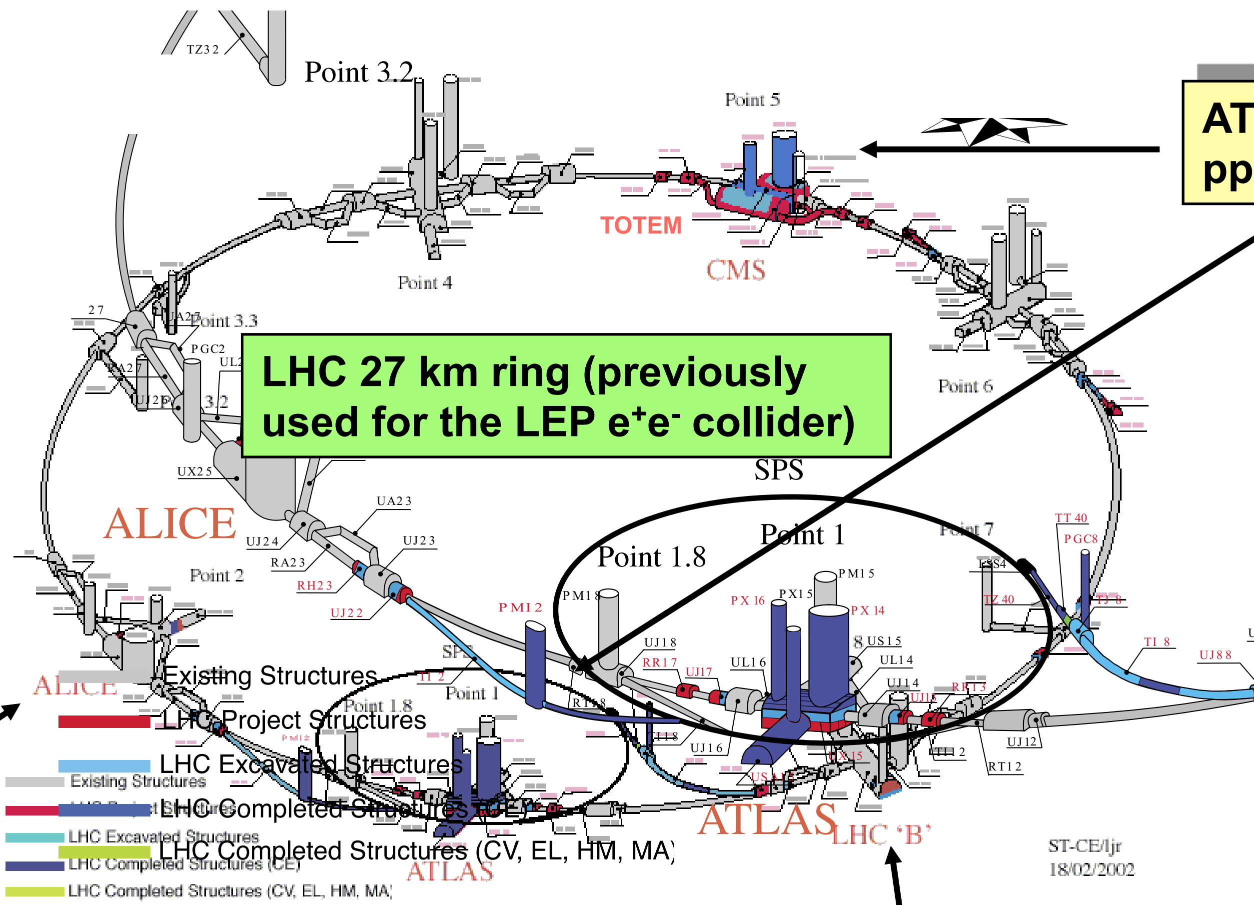
•2-particle system in its center of mass frame

•The spin-dependent interaction energy has two terms:

- •the magnetostatic energy of the two magnetic moments
- •the kinematic term due to the magnetic fields induced by the motion of the 2 particles

•Then replace the Coulomb potential $V=-\alpha/r$ by $V=kr$.

One accelerator and 4 large detectors



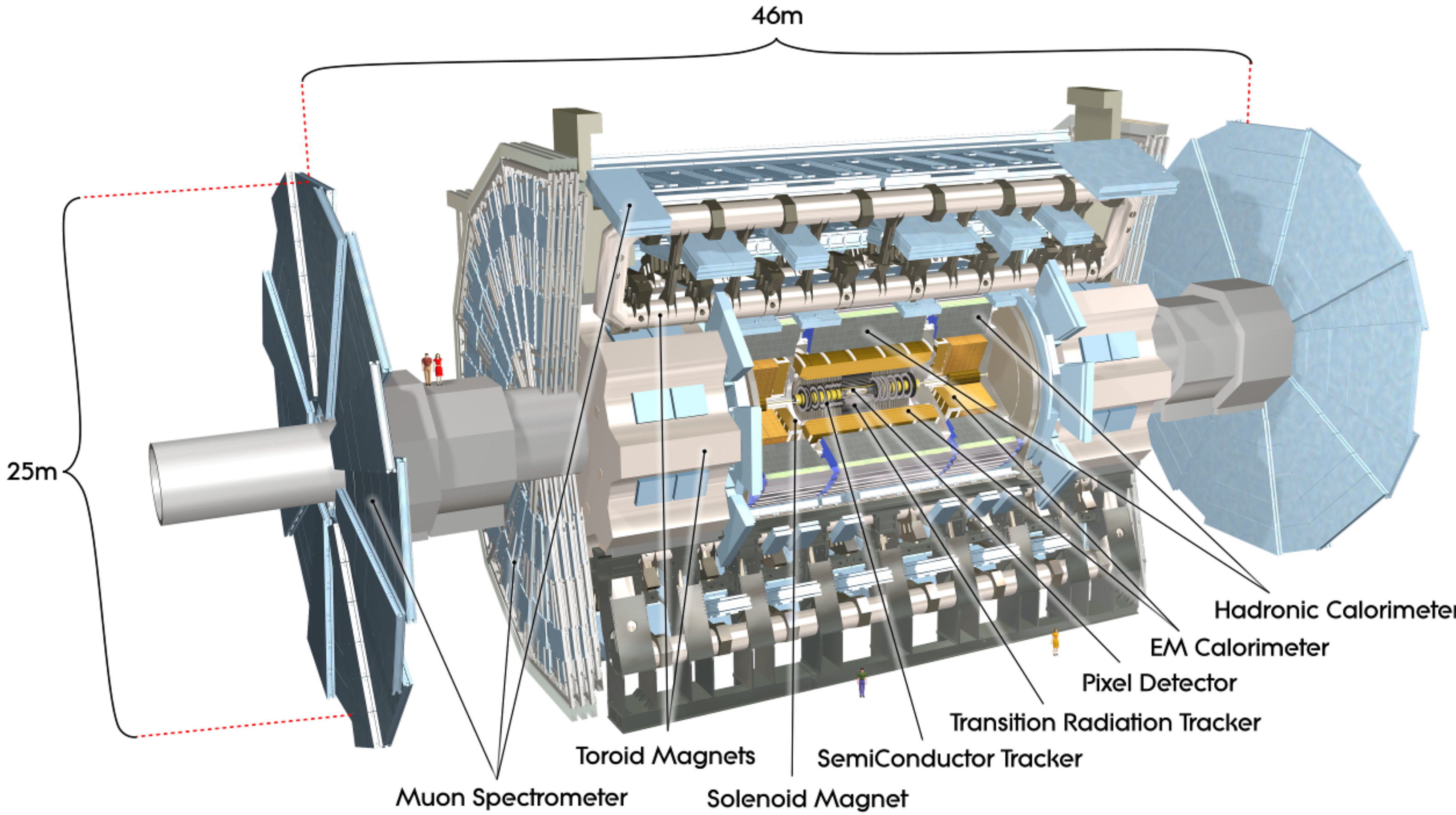
ATLAS and CMS :
pp, general purpose

LHC 27 km ring (previously used for the LEP e^+e^- collider)

ALICE :
ion-ion,
p-ion

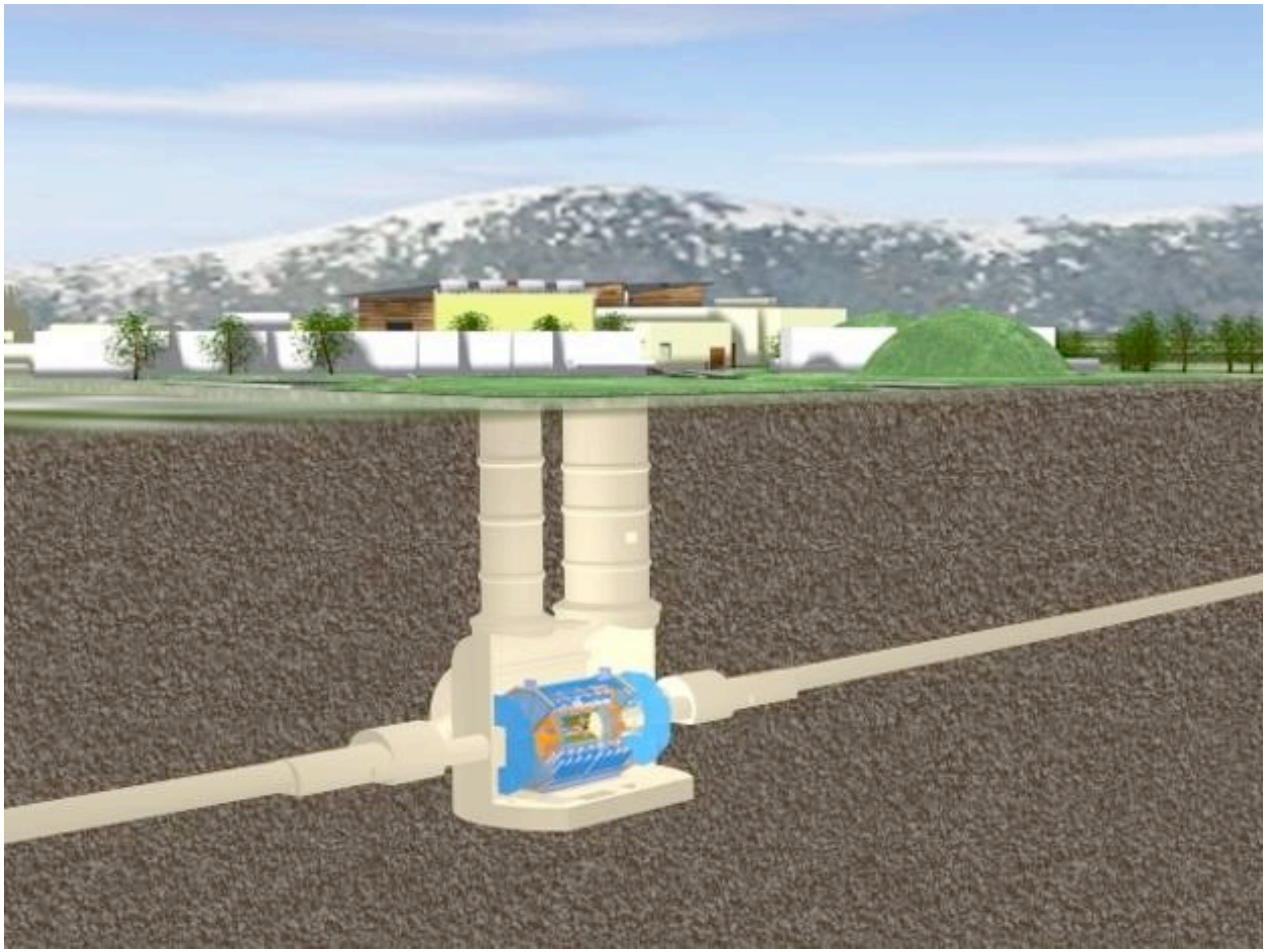
LHCb :
pp, B-physics, CP-violation

Schematic view of the ATLAS detector



Diameter	*25 m*
Barrel toroid length	*26 m*
End-cap end-wall chamber span	*46 m*
Overall weight	*7000 Tons*

The ATLAS detector was built in an underground cavern like a ship in a bottle



Cavern:

Length = 55 m
Width = 32 m
Height = 35 m
Depth = 100 m

ATLAS Collaboration

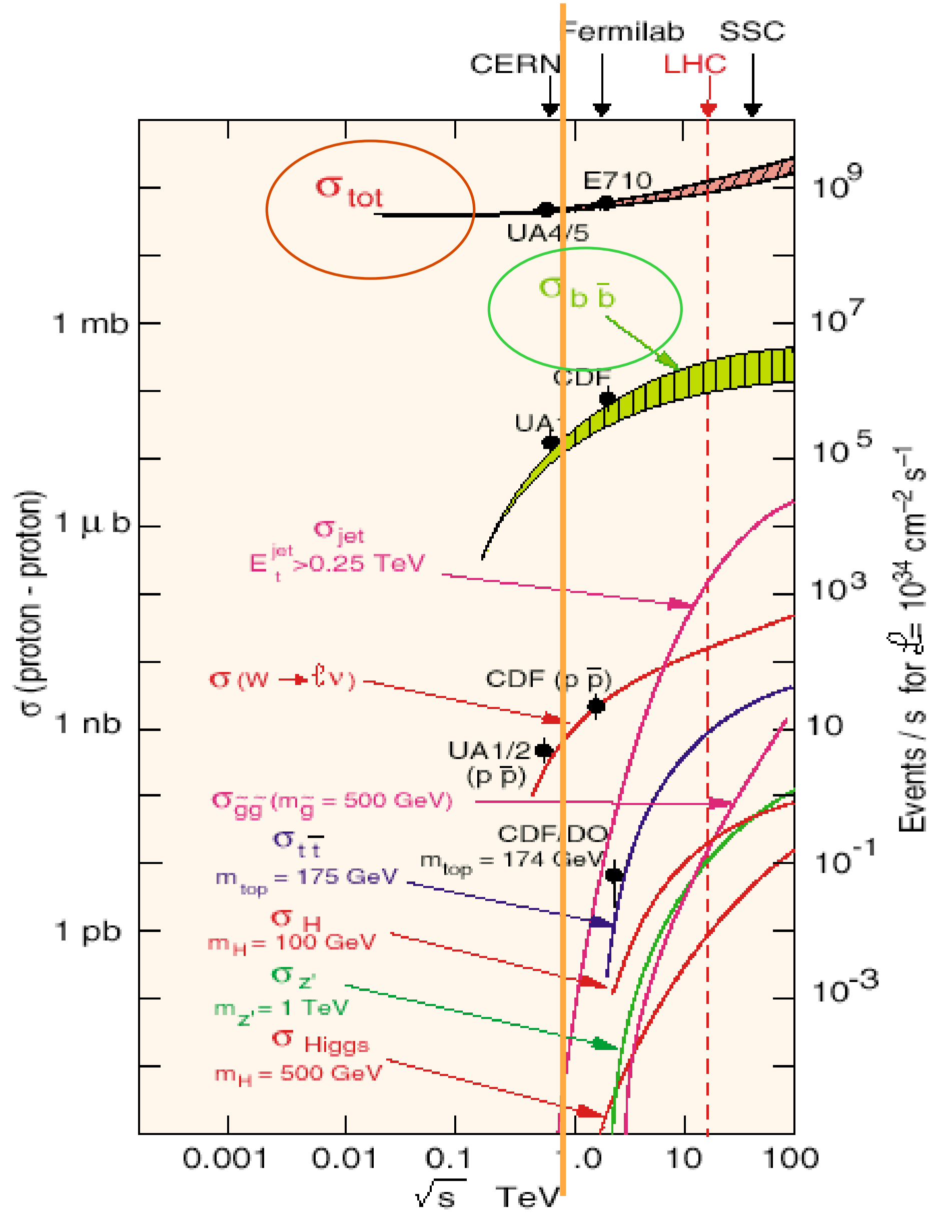
(Status May 2008)

37 Countries
167 Institutions
2235 Scientific authors

Albany, Alberta, NIKHEF Amsterdam, Ankara, LAPP Annecy, Argonne NL, Arizona, UT Arlington, Athens, NTU Athens, Baku, IFAE Barcelona, Belgrade, Bergen, Berkeley LBL and UC, HU Berlin, Bern, Birmingham, UAN Bogota, Bologna, Bonn, Boston, Brandeis, Bratislava/SAS Kosice, Brookhaven NL, Buenos Aires, Bucharest, Cambridge, Carleton, Casablanca/Rabat, CERN, Chinese Cluster, Chicago, Chile, Clermont-Ferrand, Columbia, NBI Copenhagen, Cosenza, AGH UST Cracow, IFJ PAN Cracow, DESY, Dortmund, TU Dresden, JINR Dubna, Duke, Frascati, Freiburg, Geneva, Genoa, Giessen, Glasgow, Göttingen, LPSC Grenoble, Technion Haifa, Hampton, Harvard, Heidelberg, Hiroshima, Hiroshima IT, Indiana, Innsbruck, Iowa SU, Irvine UC, Istanbul Bogazici, KEK, Kobe, Kyoto, Kyoto UE, Lancaster, UN La Plata, Lecce, Lisbon LIP, Liverpool, Ljubljana, QMW London, RHBNC London, UC London, Lund, UA Madrid, Mainz, Manchester, Mannheim, CPPM Marseille, Massachusetts, MIT, Melbourne, Michigan, Michigan SU, Milano, Minsk NAS, Minsk NCPHEP, Montreal, McGill Montreal, FIAN Moscow, ITEP Moscow, MEPhI Moscow, MSU Moscow, Munich LMU, MPI Munich, Nagasaki IAS, Nagoya, Naples, New Mexico, New York, Nijmegen, BINP Novosibirsk, Ohio SU, Okayama, Oklahoma, Oklahoma SU, Oregon, LAL Orsay, Osaka, Oslo, Oxford, Paris VI and VII, Pavia, Pennsylvania, Pisa, Pittsburgh, CAS Prague, CU Prague, TU Prague, IHEP Protvino, Regina, Ritsumeikan, UFRJ Rio de Janeiro, Rome I, Rome II, Rome III, Rutherford Appleton Laboratory, DAPNIA Saclay, Santa Cruz UC, Sheffield, Shinshu, Siegen, Simon Fraser Burnaby, SLAC, Southern Methodist Dallas, NPI Petersburg, Stockholm, KTH Stockholm, Stony Brook, Sydney, AS Taipei, Tbilisi, Tel Aviv, Thessaloniki, Tokyo ICEPP, Tokyo MU, Toronto, TRIUMF, Tsukuba, Tufts, Udine/ICTP, Uppsala, Urbana UI, Valencia, UBC Vancouver, Victoria, Washington, Weizmann Rehovot, FH Wiener Neustadt, Wisconsin, Wuppertal, Yale, Yerevan

ATLAS, the LHC, and B Physics

- LHC has a 27 km circumference, 40 kHz crossing rate
- The total $b\bar{b}$ production cross section is 500 μb: $1 b\bar{b}$ pair in every 100 collisions.
- Luminosity expectation: 10 fb^{-1} per year (@ L=$10^{33}/cm^2/s$) in Years 1-3, 100 fb^{-1} per year subsequently.



The ATLAS Detector

Tracking ($|\eta| < 2.5$, B = 2T) :

Silicon pixels and strips

Transition Radiation Detector (tracking and e /π separation)

Calorimetry ($|\eta| <5$) :

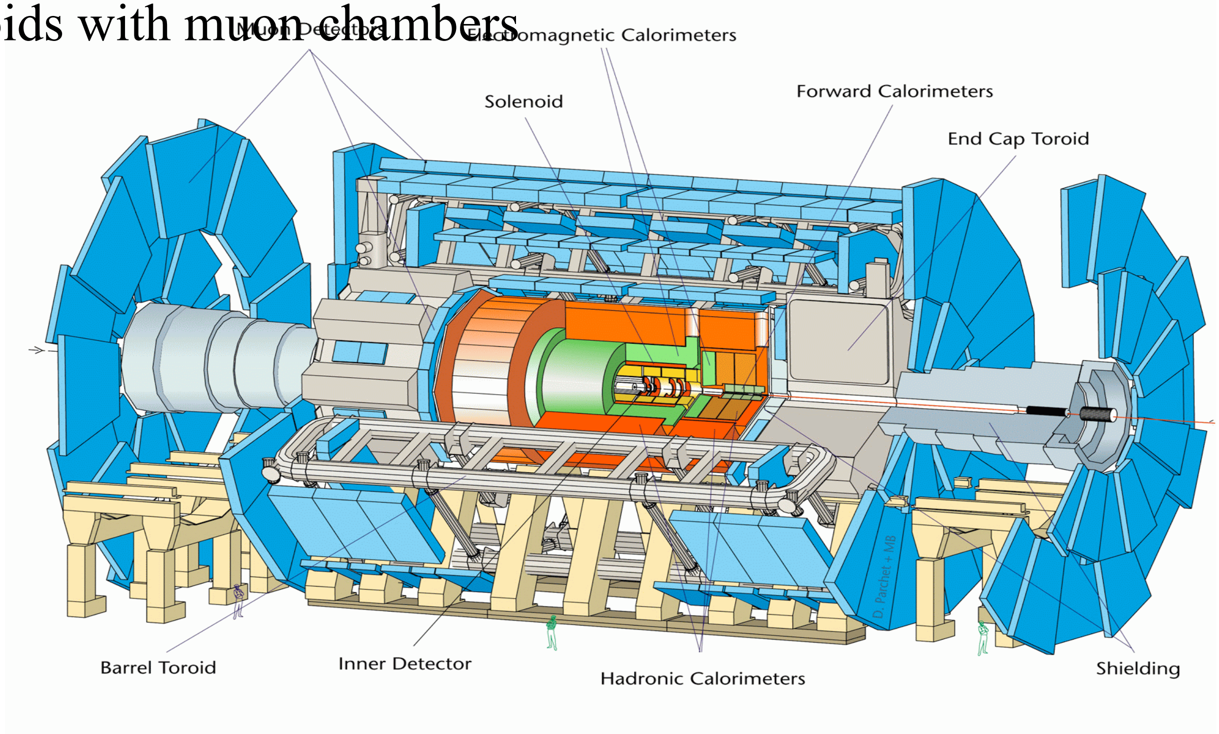
EM : Pb-LAr

HAD: Fe/scintillator (central), Cu/W-LAr (fwd)

Muon Spectrometer ($|\eta| <2.7$) :

Air-core toroids with muon chambers

- 46 m long
- 22 m diameter
- 7000 t total weight
- 2T solenoid and 0.5 T toroid
- 10^8 electronics channels
- 3000 km of cables.

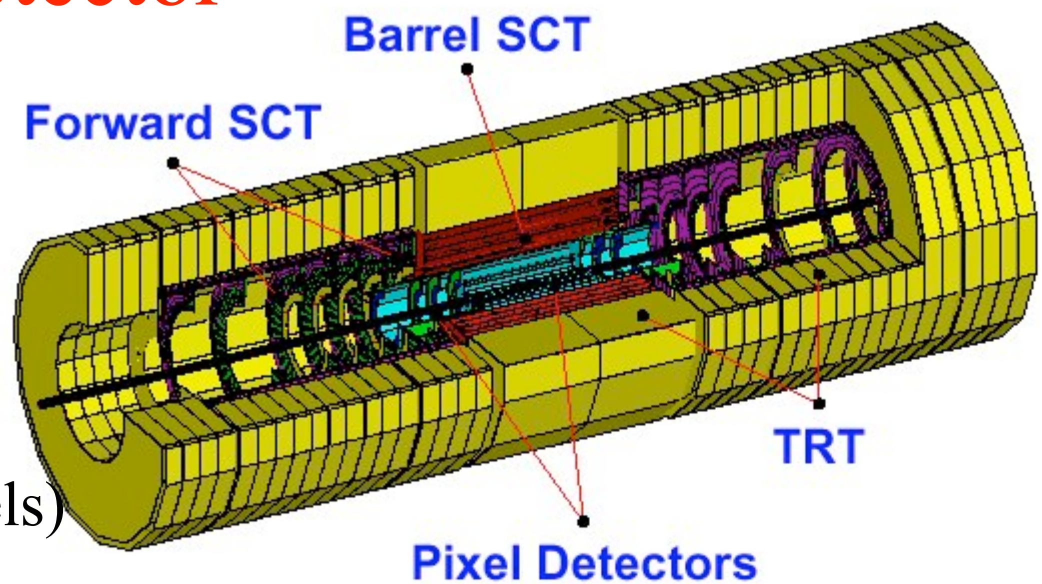


Inner Detector

Pixels:

•(0.8×10^8 channels)

•σ_φ=12 μm, σ_z=66 μm



Silicon Tracker (SCT):

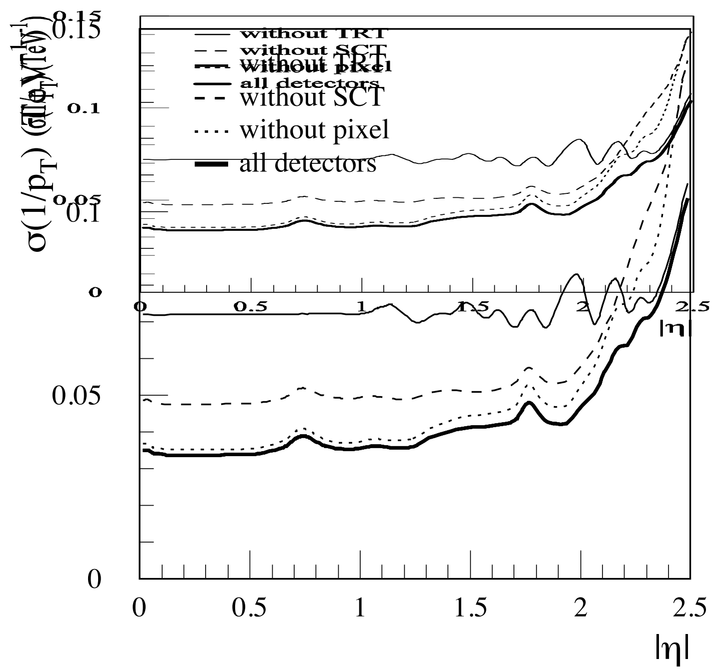
•5cm<radii<50cm (6×10^6 channels)

•σ_φ=16 μm, σ_z=580 μm

Transition Radiation Tracker (TRT)

•50<radii<100 cm (4×10^5 channels)

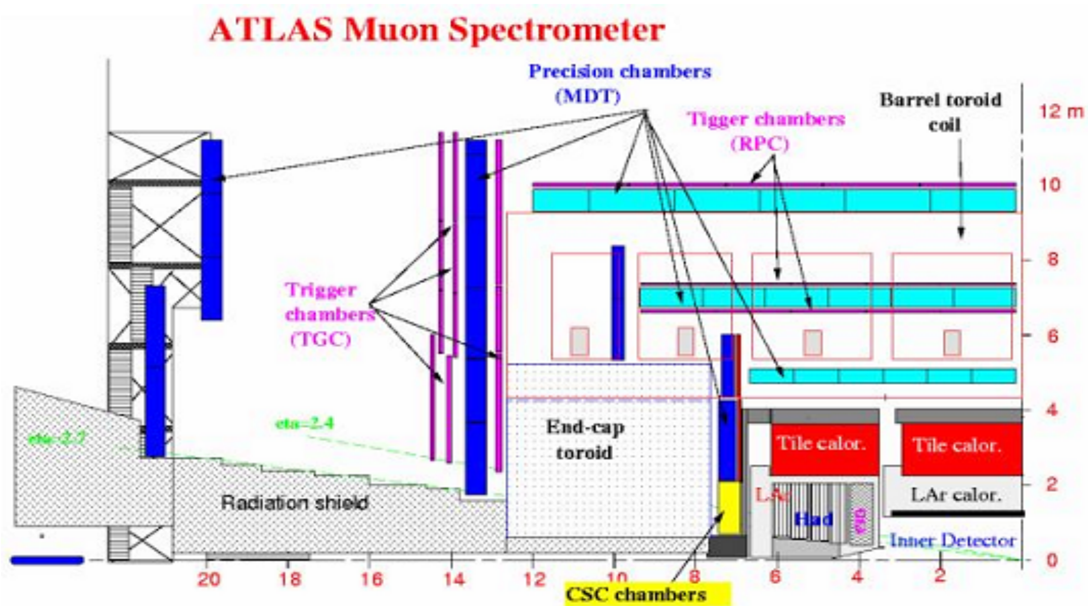
•σ=150 μm per straw

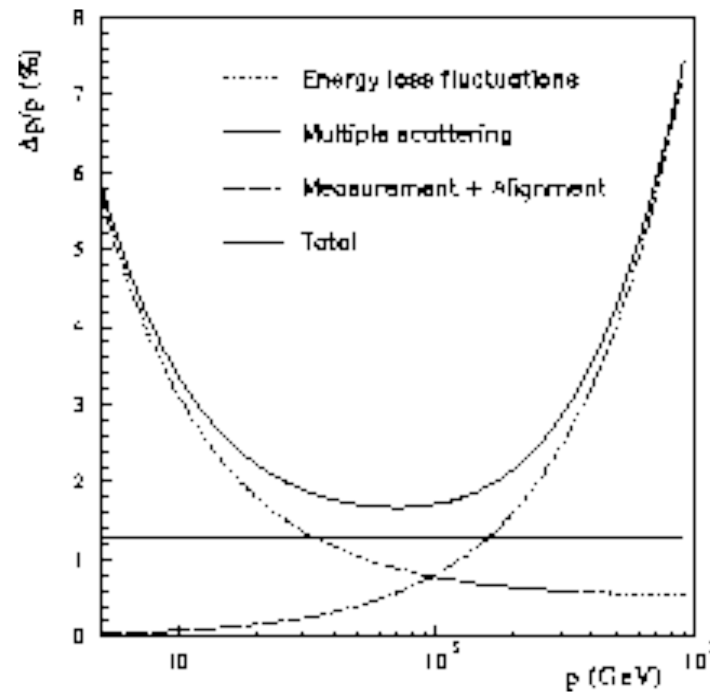


The silicon detectors provide ~ 10 azimuthal position measurements for 10 - 20μm resolution.
The TRT provides ~ 36 azimuthal position measurements for 150 microns.

Muon Spectrometer

The momentum of the muons is determined from the curvatures of their tracks in a toroidal magnetic field.





Muon tracks are identified and measured after their passage through ~2m of material.

Track measurement is made with σ = 60 μm intrinsic resolution in three precision measurement (Monitored Drift Tube) stations.